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Full-Frequency Numerical Modeling of Sound Transmission in and Radiation from Lined Ducts

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Full-Frequency Numerical Modeling of Sound Transmission in and Radiation from Lined Ducts (RP-1529)

Final Report

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Executive Summary

One of the benefits of numerical acoustics is that experiments that require special facilities and equipment, and long setup times can be simulated on the computer. This is certainly the case for assessing the attenuation of lined HVAC ducts for a number of reasons. (1) Measurements require a source room, which is normally comprised of hard walls and several loudspeakers with an aim of creating a diffuse acoustic field. (2) The HVAC duct normally terminates in a reverberant or anechoic room. The reverberant room should have low background noise since duct attenuation often exceeds 50 dB. Special care should be taken to reduce the impact of low frequency room modes. This may include adding some minimal sound absorption to the walls or using a rotating boom for measurements. (3) Test ducts must be constructed and installed between the two rooms and the space between the two rooms should have low background noise to prevent break-in.

Over the past two decades, the sound and vibration community has recognized the benefits of numerical acoustics for solving a variety of problems. Deterministic approaches like the finite and boundary element methods are now routinely used in industry to compare different product designs and assess acoustic treatments. In a prior effort for ASHRAE (RP-1218), boundary element methods were utilized to determine the attenuation of HVAC plenums (Herrin and Seybert, 2006; Herrin et al., 2007a, Herrin et al., 2007b). Results were compared to measured results from Mouratides and Becker (2003) with good agreement.

The objective of this effort is to use numerical simulation to assess both the insertion loss and breakout transmission loss of unlined and lined HVAC ducts. A coupled structural-acoustic finite element model is used. Acoustic finite elements are used to model the airspace and the lining while structural finite elements are used to model the ductwork.

All analyses were performed using the commercial software Siemens LMS Virtual.Lab. The diffuse acoustic field at the source is modeled using 20 monopole sources of random phase. A baffled termination is assumed and is modeled using a non-reflecting boundary termed an automatically matched layer. Poroelastic properties are assigned for the acoustic elements modeling the sound absorbing lining.

This report details the finite element procedures used and results are compared to data from an ongoing measurement campaign of lined square and circular ducts (RP-1408).

The major findings of this project can be summarized as follows.

- Finite element simulation of large HVAC ducts including sound absorptive lining is feasible on a PC workstation. Most analyses can be completed in a single day.

- Structural-acoustic coupling can be included in the models. However, the influence of the structure could be neglected if the engineer is primarily interested in determining the insertion loss for a lined duct.

- Breakout transmission loss can be determined both with and without sound absorptive lining. Results demonstrate that sound absorptive lining improves the breakout transmission loss at higher frequencies where the sound absorption is more effective.

- Insertion loss results were compared against measurement in 1/3-octave bands. For the most part, agreement between simulation and measurement is excellent. There are differences when the predicted insertion loss exceeds 50 dB. This occurs between 500 and 1200 Hz in some lined duct cases. Based on the current limitations due to flanking paths in test environments, measurements cannot accurately measure attenuation greater than 50 dB.

- Insertion loss is the difference between the radiated power of unlined and lined ducts so the impact of end reflections, which are included in the model, on the results should be minimal and limited to lower frequencies. The models also include the slight duct expansions where the lining is located which is likely more important.

- Breakout transmission loss was predicted using simulation and compared with the ASHRAE Handbook. ASHRAE Handbook results are from measurement. For the most part, agreement is excellent between the Handbook and simulation for both circular and rectangular duct cross-sections. However, there are sizeable differences between simulation and the ASHRAE Handbook at low frequencies for circular ducts. Similar differences between analytical models and measurement have been observed in past literature. The reason for the discrepancy is that the predicted breakout transmission loss is in excess of 50 dB which likely exceeds the measurement test limits due to flanking paths.

- By plotting the attenuation (in dB) from the start of the test duct versus the number of wavelengths, it can be observed that attenuation is steep and relatively linear for the first 5 acoustic wavelengths. After which, the attenuation rate is reduced though it is still approximately linear. These results suggest that simple relationships for duct attenuation could be established for the standard duct sizes that are summarized in the *ASHRAE Handbook – HVAC Applications* (2015). Results demonstrate that the ASHRAE Handbook tables are inadequate for ducts which are longer than 3.05 m (10 ft). Specifically, ASHRAE Handbook insertion loss predictions are overly high because they assume a linear attenuation per unit length irrespective of the total length of lined duct.

In summary, numerical simulation has been successfully used to determine both insertion loss and breakout transmission loss with acceptable accuracy. For future work, the models should be used to update and expand the information in the *ASHRAE Handbook – HVAC Applications* (2015). The models can certainly be used to extend the tables to ducts exceeding 3.05 m (10 ft) in length. In addition, the frequency resolution of the tables can be refined from octave bands to 1/3-octave bands.

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1. Introduction

Noise is one of many design concerns that must be attended to in buildings. If unaddressed, mitigation measures are costly after the building is in place and the effectiveness of measures taken is reduced. Likely, the most important sources of noise are from HVAC equipment, and one of the dominant paths is airborne transmission through ducts. Breakout noise is an important secondary path.

Most of the past work has been performed experimentally. However, measurements require special facilities and expensive measurement equipment. Prior measurement studies, though valuable, have only looked at a subset of the ranges of duct cross-sectional areas, lengths, and sound absorptive liners. Accordingly, there is a great need for a validated numerical approach that can be used to analyze the full range of HVAC ducting in use.

This report documents a finite element approach to determine the insertion loss and breakout transmission loss of unlined and lined ducts, elbows, and side branches. Results are validated using measurement where available or the *ASHRAE Handbook – HVAC Applications* (2015). The developed and validated model can accommodate the full range of HVAC ducts. Accordingly, it can be used to 1) conduct sensitivity studies on standard sized ducting to supplement the information in the *ASHRAE Handbook*, 2) evaluate the attenuation of standard HVAC elements like plenums, baffled silencers, elbows, and side branches, and 3) assess the attenuation of built-up HVAC systems.

As a prelude, the following sections detail the past measurement and analysis work that has been conducted on unlined and lined ducts, elbows, and side branches.

2. Background

2.1 Lined Duct Attenuation

Often, the most effective treatment is to add fiber lining to the interior duct surfaces which adds thermal insulation and has little effect on the pressure drop. Not surprisingly, ASHRAE had devoted a number of research projects to better understanding noise attenuation in ducts and lined ducts in particular. Vér (1978) reviewed a number of prior experimental studies on duct attenuation and compared results to the 1973 and 1976 ASHRAE Handbooks. At the time, Vér (1978) pointed out 1) the need for more careful experimentation, 2) that sound absorption properties for common linings were unknown, and 3) that effects of flanking and transmission through duct walls were not well understood.

In the next decade, Machen and Haines (1983) and Kuntz and Hoover (1987) performed extensive measurement campaigns. The results of Machen and Haines appear to form the basis for the rectangular duct insertion loss data in the *ASHRAE Handbook – HVAC Applications* (2015). Kuntz and Hoover measured the insertion loss and in-duct attenuation for 18 unlined and lined ducts of varying rectangular cross-section. Each of the tested ducts was 10 ft (3.05 m) in length. Their results are consistent with, though not identical, to the tables in the Handbook.

In follow on work, Reynolds and Bledsoe (1989a, 1989b) used regression analysis to determine equations for the sound attenuation of lined and unlined rectangular and circular ducts. The latter paper provided results for the insertion loss of 20 ft (6.10 m) length circular ducts and may be the basis for the circular duct information in the ASHRAE Handbook. To the authors' knowledge, the regression equations have not been widely used by the ASHRAE community.

At this juncture, the ASHRAE Handbook provides tables for the attenuation of lined and unlined ducts of a variety of cross-sections. However, Kuntz and Hoover limited their studies to ducts that are 10 ft (3.05 m) in length, and their suitability for longer ducts is suspect. Recently, Reynolds (2015) in RP-1408 has performed a far more extensive measurement campaign than had previously been undertaken considering different duct lengths, and circular and rectangular cross-sections. This data will likely be the basis for future ASHRAE Handbook editions.

2.2 Elbow and Side Branch Attenuation

Though the most effective way to reduce the noise is to use sound absorptive lining in the ducts or introduce plenums, there is also modest attenuation at elbows or when other ducts branch off the main duct. Sound is reflected back towards the source at a bend due to the slight change in cross-sectional area. There will be less attenuation if turning vanes are present. In contrast, the attenuation can be greatly increased if lining is added to the elbow.

Cabelli (1980) developed analytical models for unlined mitered and curved 90° bends, and Ko and Ho (1977) looked at curved bends. Vér (1983a) summarized results presented by Mechel (1975) and from a VDI Technical Report (2001) for different bends in a form appropriate for HVAC engineers. Vér's (1983a) work forms the basis for what is currently in the ASHRAE Handbook (2015).

Almost all of the prior measurement studies have assumed a 90° bend though bends of various angles are commonly seen in practice. Accordingly, a validated numerical simulation approach is of interest for application to the full range of elbows encountered in practice.

2.3 Breakout Transmission Loss

Though the direct airborne path is dominant, breakout noise is an important secondary path especially if ductwork is exposed. Breakout noise occurs when internal duct noise causes the duct walls to vibrate and in turn radiate noise to their surroundings and is normally a greater concern at low frequencies (Cummings, 1985). Turbulence may also cause ducts to rumble but this is not breakout noise in the strict sense. Breakout noise is most commonly reduced by using spiral wound circular ducts instead of rectangular ducts or by adding sound absorptive lining.

Both Vér (1983b) and Cummings (1983,1985) investigated breakout noise in ASHRAE supported efforts. Cummings continued working in the area for the next two decades and his work and others is summarized in his comprehensive review paper (Cummings, 2001). That paper nicely synopsizes the current state-of-the-art and is written at the level of a